

Electronically tunable color filter with surface plasmon waves

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Abstract

Last year, I had reported a novel phenomenon of voltage-induced color-selective absorption with surface plasmons (Appl. Phys. Lett. 67, 1749). When a white light is incident on a metal/ITO material interface, in certain condition, surface plasmon waves can be excited; those photons in surface plasmon resonance wavelength range would be totally absorbed and these photons out of the surface plasmon resonance wavelength range would be almost totally reflected. This surface plasmon resonance depends on the dielectric constants of both the metal and the ITO material. If a voltage is added on the ITO material to change its dielectric constant, the surface plasmon resonance spectrum can be shifted from one wavelength to the other, and this is a tunable notch filter. If coupled surface plasmon waves are used, a tunable bandpass filter can be built.

A prototype mode has been built using liquid crystal as the ITO material. Experiment result, which has excellent agreement with theory, has shown that the wavelength tunable range can cover almost all of the visible (from 450 nm to 650 nm) when 30-v voltage is applied. Theoretical calculation has shown that this tunable filter can also work in IR range up to at least 10 μm .

Keywords: Surface plasmons, tunable filter, electro-optics, thin film, image spectrometer

An image spectrometer acquires images of the same scene simultaneously in many contiguous spectral bands over a given spectral range. By adding wavelength to the image as a third dimension, the spectrum of any pixel in the scene can be calculated. These images can be used to obtain the reflectance spectrum for each image pixel, which can be used to identify components in the target.

The most common method of doing image spectroscopy is by changing fixed dichroic filters, the system is heavy and the speed is slow. Several tunable filters have been proposed, but they all have severe problems, for example, the acousto-optic tunable filter is power hungry (in kilowatts), the liquid crystal tunable filter is slow and has low efficiency, the Fabry-Perot tunable filter has a very narrow tunable range. Now a new technology of surface plasmon tunable color filter has been invented at JPL, surface plasmon tunable filter is a light weight, low power, high efficiency device, it can be integrated with a solid state sensor for an imaging spectrometer on a chip.

The surface plasmon (SP) has been studied since the 1960's. It can be described as a collective oscillation in electron density at the interface of a metal and a dielectric.¹ At SP resonance, the reflected light vanishes. This resonance is referred to as attenuated total reflection, and is dependent upon the dielectric constants of both the metal and the dielectric. If an electro-optical (EO) material is used as the dielectric and a voltage is applied to change the SP resonance condition, the reflected light can be modulated^{2,3}. A SP spatial laser light modulator with a contrast ratio greater than 100 has been reported⁴.

If we consider the SP light modulator in frequency space, the photons at the SP resonance frequency will be absorbed by the free electrons in the metal, and the photons away from the SP resonance will be totally reflected. If a voltage is applied to the EO material, the resonance frequency will change, and a tunable filter is formed.

The SP tunable notch filter⁵ was invented in 1992, and a prototype model was built in 1993. The experimental result was published in 1995 as a new physical phenomenon of "voltage-induced color-selective absorption with surface plasmons"⁶.

The experiment arrangement of the SP tunable notch filter is shown in Fig. 1. Here a 50 nm silver layer was used as the metal film and a 4 μ thick liquid crystal layer was used as the EO material. When p-polarized white light is incident on the metal/liquid crystal interface through the coupling prism, SP waves can be excited. The photons in the SP resonance range will be taken out of the reflection spectrum. When a voltage is

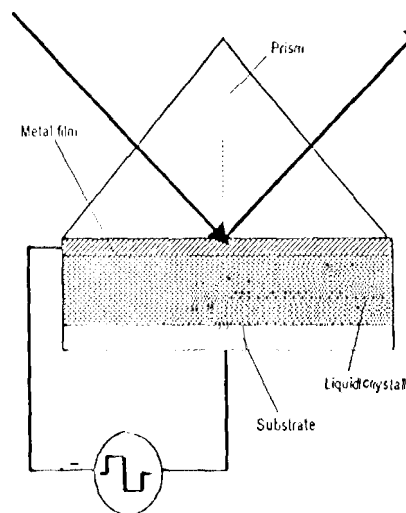


Fig. 1 Experiment arrangement of surface plasmon tunable notch filter.

liquid crystal will change, the S_1' resonance will change, and the color of the reflected light will change. The experimental result is shown in Fig. 2. Here the dots are the experiment data and the solid curves are the theoretical calculations. When a white light was incident on this sample at zero voltage, the S_1' resonance was at 640 nm, the red color was absorbed and the reflected light looked cyan. When a 10-V voltage was applied, the resonance shifted to 560 nm, green color was absorbed, and the reflected light looked magenta. When the voltage was increased to 30-v, the S_1' resonance shifted to 450 nm, blue color was absorbed and the reflected light looked yellow. The experiment had shown very good agreement with the theory

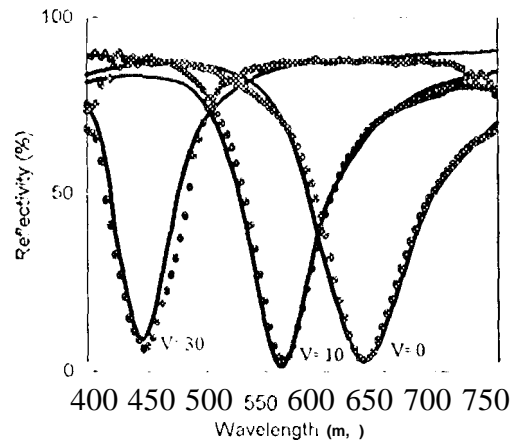


Fig. 2 Voltage-induced color selection with 50 nm silver film. When the applied voltage increases, the absorption band shifts toward lower wavelength.

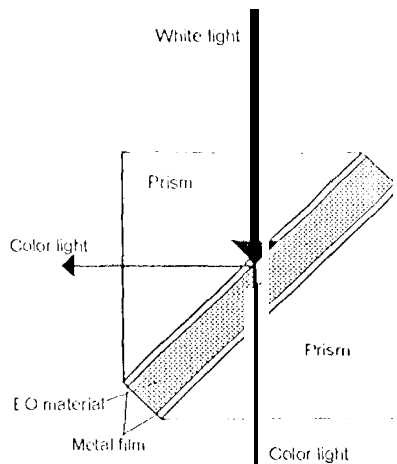


Fig. 3 Structure of surface plasmon bandpass filter

wave with the same frequency at the other ITO/metal interface because of the symmetric structure. The resonance photons will then be re-radiated out as the transmittal light. When a voltage is added on the ITO material, the index of the ITO material will change, the S_1' resonance frequency will change, and the transmission spectrum will change. Fig. 4 shows the theoretical calculation of transmission spectrum for two silver film separated by a 150 nm ITO material layer. Without voltage, the index change Δn is zero, and the peak transmission is at 450 nm. When the voltage induced index change of the ITO layer has a increase of $\Delta n = 0.2$, the transmission peak shifts to 530 nm. When the index change $\Delta n = 0.5$, the peak transmission shifts to 650 nm.

The intensity of peak transmission depends on the optical properties and the thickness of

In 1996, the S_1' tunable bandpass filter using coupled S_1' waves was invented at JYJ. The structure of this SP tunable bandpass filter is shown in Fig. 3. A symmetric geometry of metal/ITO/metal is employed. Two high index glass prisms are used for the coupling. A thin metal film is evaporated on each prism respectively. A thin ITO material layer is sandwiched by the two prisms. The ITO layer is less than one wavelength thick. When a S_1' wave is excited on one side of metal/ITO material interface by the incident photons, the energy of resonance photons will be converted into the motion of free electrons of the metal film, the optical field will penetrate the thin ITO layer and excite another SP

the metal. Metals with small imaginary part of the dielectric constant will have higher peak transmission and narrower bandwidth. On the other hand, a thinner metal layer will give greater peak transmission] and broader bandwidth.

The operation spectrum range is also depends on the optical property of the metal film, silver seems a good choice in visible, while gold, potassium and lithium may be function well in the IR range. Theoretical calculation shows that surface plasmon tunable can work in the IR range to least 8 micron.

Because surface plasmon tunable filter is a voltage device, it needs a little power to operate, and if two micro-prism arrays are used to replace the two prisms, it will be a light weight device. Currently, an effort of combining surface plasmon tunable filter and active pixel sensor to form an imaging spectrometer on a chip is underway.

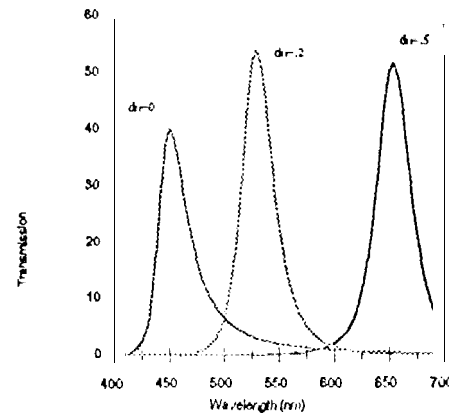


Fig. 4 When the EO material has an index change of 0.5, the transmission shifts from 450 nm to 650 nm.

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